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Extension of Finitely Conducting Earth-Image-Theory Results To Any Range

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Preface

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Finitely conducting earth-image-theory techniques have been employed to determine new formulas for the electric and magnetic fields produced by the four elementary dipole antennas for the air-to-air, surface-to-air, air-to-surface, and surface-to-surface propagation cases. The only restriction on the use of these formulas is that the index of refraction be large (i.e., $|n^2| \geq 10$). They are valid at any frequency and at any range for the flat-earth case. These formulas reduce to previously derived results when either

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(the absolute value of n squared > or = 10)

20. (Cont'd)

(1) the measurement distance is much less than a free-space wavelength, (2) the Sommerfeld numerical distance is small, or (3) the measurement distance is much greater than an earth-skin depth.

In terms of computer time, these new formulas can be evaluated in fractions of a minute compared with hours for the complete numerical evaluation of the exact Sommerfeld integrals.

These formulas are intended to supplement the author's recently derived subsurface-to-subsurface and air-to-air propagation formulas.

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GLOSSARY OF SYMBOLS

A	$\dfrac{\sin\psi_1 + \Delta F(w)}{\sin\psi_1 + \Delta} = \left(\dfrac{1 + \Gamma_{11}}{2}\right) + \left(\dfrac{1 - \Gamma_{11}}{2}\right)F(w)$
B	$\dfrac{\sin^2\psi_1 - \Delta^2 F(w)}{\sin\psi_1 + \Delta} = \left(\dfrac{1 + \Gamma_{11}}{2}\right)\sin\psi_1 - \left(\dfrac{1 - \Gamma_{11}}{2}\right)\Delta F(w) = \sin\psi_1 - \Delta A$
D	$(\rho^2 + h^2)^{1/2}$ (meters)
D_i	$[\rho^2 + (d + h)^2]^{1/2}$ (meters)
d	$\sim 2/\gamma_1$ for $\lvert n^2\rvert >> 1$, complex image depth (meters)
E_ρ	Horizontal electric-field component in the ρ direction (volts/meter)
E_ϕ	Horizontal electric-field component in the ϕ direction (volts/meter)
E_z	Vertical electric-field component (volts/meter)
F(w)	Or $F(w_0)$, Sommerfeld surface-wave attenuation factors
h	Height ($h \geq 0$) of transmitting antenna with respect to earth's surface (meters)
HED	Horizontal electric dipole
HMD	Horizontal magnetic dipole
H_ρ	Horizontal magnetic-field component in the ρ direction (amperes/meter)
H_ϕ	Horizontal magnetic-field component in the ϕ direction (amperes/meter)
H_z	Vertical magnetic-field component (amperes/meter)
I	Current (amperes)
$J_0(\lambda\rho)$	Bessel function of the first kind, order zero, with argument $\lambda\rho$
m	Magnetic dipole moment (ampere-meters^2)
n	γ_1/γ_0, index of refraction
p	Electric current moment (ampere-meters)
R	$(\rho^2 + z^2)^{1/2}$ (meters)
R_0	$[\rho^2 + (z - h)^2]^{1/2}$ (meters)

R_1	$[\rho^2 + (z + h)^2]^{1/2}$ (meters)
R_2	$[\rho^2 + (d + z + h)^2]^{1/2}$ (meters)
R_i	$[\rho^2 + (d + z)^2]^{1/2}$ (meters)
t	Time (seconds)
u_0	$(\lambda^2 + \gamma_0^2)^{1/2}$ (meters^{-1}) (air)
u_1	$(\lambda^2 + \gamma_1^2)^{1/2}$ (meters^{-1}) (earth)
VED	Vertical electric dipole
VMD	Vertical magnetic dipole
w	Or w_0, Sommerfeld numerical distances
z	Height ($z \geq 0$) of receiving antenna with respect to earth's surface (meters)
$\Gamma_{\parallel}$	$-\dfrac{\sin\psi_1 - \Delta}{\sin\psi_1 + \Delta}$ for $\lvert n^2\rvert >> 1$, Fresnel reflection coefficient for vertical polarization
γ_0	$(-\omega^2\mu_0\epsilon_0)^{1/2} = i2\pi/\lambda_0$, upper half-space (air) propagation constant (meters^{-1})
γ_1	$(i\omega\mu_1\sigma_1 - \omega^2\mu_1\epsilon_1)^{1/2}$, lower half-space (earth) propagation constant (meters^{-1})
Δ	$\gamma_0/\gamma_1 = 1/n$
δ	$\left(\dfrac{2}{\omega\mu_0\sigma_1}\right)^{1/2}\left\{\left(\dfrac{\omega^2\epsilon_1^2}{\sigma_1^2} + 1\right)^{1/2} - \dfrac{\omega\epsilon_1}{\sigma_1}\right\}^{-1/2}$ skin depth in the water or earth (meters)
ϵ_0	$\simeq 10^{-9}/36\pi$ farads/meter, permittivity of free space
ϵ_1	Permittivity of lower half-space (earth) (farads/meter)
λ	Dummy integration variable in the basic Sommerfeld integrals (meters^{-1})
λ_0	Free-space wavelength (meters)
ρ	$(x^2 + y^2)^{1/2}$, radial distance in a cylindrical coordinate system (meters)
ρ_i	$(\rho^2 + d^2)^{1/2}$ (meters)
σ_1	Conductivity of the lower half-space (earth) (Siemens/meter)
ϕ	$\tan^{-1}(y/x)$, azimuth angle in a cylindrical coordinate system

$\mu \approx \mu_0$	$= 4\pi \times 10^{-7}$ henries/meter, permeability of free space
ψ	$\tan^{-1}(z/\rho)$ or $\tan^{-1}(h/\rho)$, elevation angle
ψ_i	$\tan^{-1}\left(\frac{d+z}{\rho}\right)$ or $\tan^{-1}\left(\frac{d+h}{\rho}\right)$ or $\tan^{-1}\left(\frac{d}{\rho}\right)$, elevation angle
ψ_0	$\tan^{-1}\left(\frac{z-h}{\rho}\right)$, elevation angle
ψ_1	$\tan^{-1}\left(\frac{z+h}{\rho}\right)$, elevation angle
ψ_2	$\tan^{-1}\left(\frac{d+z+h}{\rho}\right)$, elevation angle
ω	$2\pi f$ radians/second, angular frequency

EXTENSION OF FINITELY CONDUCTING EARTH-IMAGE THEORY RESULTS TO ANY RANGE

INTRODUCTION

During the past several years, finitely conducting earth-image theory techniques have proved quite useful in determining the quasi-static fields of antennas located near the earth's surface for both single-layered and multi-layered earths. (For detail references, see Bannister.[1,2]) The quasi-static range is defined as that range where the measurement distance is much less than a free-space wavelength.

Physically, the essence of the quasi-static-range finitely conducting earth-image theory technique is to replace the finitely conducting earth by a perfectly conducting earth located at the (complex) depth d/2, where $d = 2/\gamma_1$ and $\gamma_1 = [i\omega\mu_0(\sigma_1 + i\omega\varepsilon_1)]^{1/2}$ is the propagation constant in the earth (see figure 1 for the image-theory geometry). Analytically, this corresponds to replacing the algebraic "reflection coefficient," $(u_1 - \lambda)/(u_1 + \lambda)$, in the exact integral expressions with $\exp(-\lambda d)$, where λ is the variable of integration.[3] For antennas located at or above the earth's surface, the general image-theory approximation is valid throughout the quasi-static range.[1,2]

Recently[2,4] we have shown, for horizontally polarized sources, that finitely conducting earth-image theory techniques are not limited to the

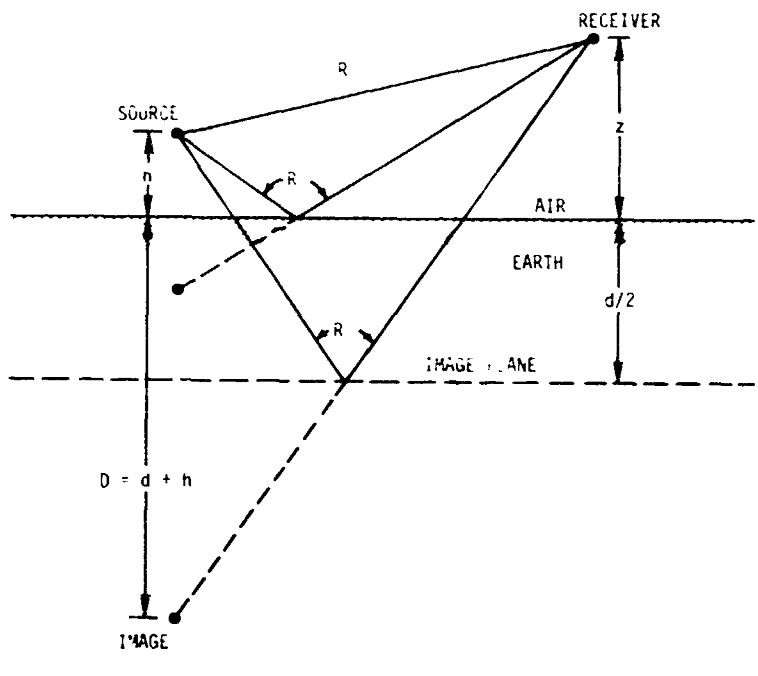

Figure 1. Image-Theory Geometry

quasi-static range alone. That is, by replacing the horizontally polarized algebraic "reflection coefficient," $(u_1 - u_0)/(u_1 + u_0)$, with $\exp(-u_0 d)$, we demonstrated that finitely conducting earth-image theory techniques can be utilized at any range from the source. Mohsen[5] has validated and extended these results to include higher-order terms that correspond to multiple images at the same location. Mahmoud and Metwally,[6] employing discrete and discrete-plus-continuous images, have computed satisfactorily the change in the input impedance of a vertical magnetic dipole (VMD) due to the presence of the earth.

We have also recently shown[7,8] that, for small Sommerfeld numerical distances, nearfield and farfield range finitely conducting earth-image theory techniques can also be employed for determining the fields produced by horizontal electric dipole (HED) and horizontal magnetic dipole (HMD) antennas (which are a combination of vertically and horizontally polarized sources.

It is the purpose of this report to extend the use of finitely conducting earth-image theory techniques to any range and to present new formulas for the electric and magnetic fields produced by the four elementary dipole antennas for the air-to-air, surface-to-air, air-to-surface, and surface-to-surface propagation cases. The only restriction on the use of these formulas is that $|n^2| \geq 10$, where $n = \gamma_1/\gamma_0$. They are valid at any frequency and at any range for the flat-earth case. These formulas reduce to the author's previously derived results when either (1) the Sommerfeld numerical distance is small,[7,8] (2) the measurement distance is much less than a free-space wavelength,[1,2] or (3) the measurement distance is much greater than an earth-skin depth.[9]

In this report, the four elementary dipole antennas [vertical electric dipole (VED), VMD, HED, and HMD] are situated at height h ($h \geq 0$) with respect to a cylindrical coordinate system (ρ,ϕ,z) and are assumed to carry a constant current, I. The axes of the VED and HED (of dipole moment p) are oriented in the z and x directions, respectively, while the axes of the VMD and HMD (of dipole moment m) are oriented in the z and y directions, respectively. The earth, which is assumed to be a homogeneous medium with conductivity σ_1 and dielectric constant ϵ_1 $(= \epsilon_r\epsilon_0)$, occupies the lower half-space ($z < 0$) and the air occupies the upper half-space ($z > 0$). The magnetic permeability of the earth is assumed to equal μ_0, the permeability of free space. Meter-kilogram-second (MKS) units are employed and a suppressed time factor of $\exp(i\omega t)$ is assumed.

AIR-TO-AIR PROPAGATION DERIVATION PROCEDURE

As an example of our derivation procedure, consider an HED source. When h and z are ≥ 0, the Sommerfeld integral expressions for the HED Hertz vector are[10-12]

$$\Pi_x = \frac{p}{4\pi i\omega\epsilon_0}\left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + 2\int_0^\infty \frac{e^{-u_0(z+h)}}{u_1 + u_0} J_0(\lambda\rho)\lambda d\lambda\right] \tag{1}$$

and

$$\Pi_z = \frac{p \cos \phi}{4\pi i\omega\varepsilon_0} \times \frac{\partial}{\partial\rho}\int_0^\infty \frac{2(u_1 - u_0)}{\gamma_1^2 u_0 + \gamma_0^2 u_1} e^{-u_0(z+h)} J_0(\lambda\rho)\lambda d\lambda \ , \tag{2}$$

where

$R_0^2 = \rho^2 + (z - h)^2,$

$R_1^2 = \rho^2 + (z + h)^2,$

$u_0^2 = \lambda^2 + \gamma_0^2,$

$u_1^2 = \lambda^2 + \gamma_1^2,$

$\gamma_0^2 = -\omega^2\mu_0\varepsilon_0$, and

$\gamma_1^2 = i\omega\mu_0(\sigma_1 + i\omega\varepsilon_1).$

From equations (1) and (2), utilizing the identity $(u_1 - u_0)(u_1 + u_0) = \gamma_1^2 - \gamma_0^2$, we have

$$\vec{\nabla} \cdot \vec{\Pi} = \frac{p \cos \phi}{4\pi i\omega\varepsilon_0} \times \frac{\partial}{\partial\rho}\left[\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \int_0^\infty \frac{2\gamma_0^2 e^{-u_0(z+h)}}{\gamma_1^2 u_0 + \gamma_0^2 u_1} J_0(\lambda\rho)\lambda d\lambda\right] . \tag{3}$$

For $|n^2| >> 1$, we have shown that[2 4,7,8]

$$\frac{u_1 - u_0}{u_1 + u_0} \sim e^{-u_0 d} \tag{4}$$

and

$$1 - \left(\frac{u_1 - u_0}{u_1 + u_0}\right) = \frac{2u_0}{u_1 + u_0} \sim 1 - e^{-u_0 d} \ , \tag{5}$$

where

$$d \sim 2/\gamma_1 \ . \tag{6}$$

If we use equations (1) and (5) and Sommerfeld's integral,[11]

$$S_1 = \int_0^\infty e^{-u_0(z+h)} J_0(\lambda\rho)\frac{\lambda}{u_0} \times d\lambda = \frac{e^{-\gamma_0 R_1}}{R_1} \tag{7}$$

results in[2,7,8]

$$
\Pi_x = \frac{I\ell}{4\pi i\omega\varepsilon_0}\left(\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{e^{-\gamma_0 R_1}}{R_1} - \frac{e^{-\gamma_0 R_2}}{R_2}\right)
$$

$$
= \frac{I\ell}{4\pi i\omega\varepsilon_0}\left(\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_2}}{R_2}\right) , \tag{8}
$$

where $R_2^2 = \rho^2 + (d + z + h)^2$. This equation is valid at any range from the source.

Since $\gamma_0^2/\gamma_1^2 = \Delta^2 = 1/n^2$, equation (3) can be rewritten as

$$
\vec{\nabla} \cdot \vec{\pi} = \frac{p \cos \phi}{4\pi i\omega\varepsilon_0} \times \frac{\partial}{\partial\rho}\left(\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + I_{DIV}\right) , \tag{9}
$$

where

$$
I_{DIV} = \int_0^\infty \frac{2\Delta^2 e^{-u_0(z+h)}}{u_0 + \Delta^2 u_1} J_0(\lambda\rho)\lambda d\lambda \ . \tag{10}
$$

Since

$$
\frac{1}{u_0 + \Delta^2 u_1} = \frac{1}{u_0} - \left(\frac{1}{u_0} - \frac{1}{u_0 + \Delta^2 u_1}\right) = \frac{1}{u_0} - \frac{\Delta^2 u_1}{u_0(u_0 + \Delta^2 u_1)} , \tag{11}
$$

then, from equations (7) and (11),

$$
I_{DIV} = 2\Delta^2\left[\frac{e^{-\gamma_0 R_1}}{R_1} - \int_0^\infty \frac{\Delta^2 u_1 e^{-u_0(z+h)}}{u_0(u_0 + \Delta^2 u_1)} J_0(\lambda\rho)\lambda d\lambda\right] \tag{12}
$$

$$
= \begin{bmatrix}\text{small Som-}\\ \text{merfeld}\\ \text{numerical}\\ \text{distance}\\ \text{term}\end{bmatrix} + \begin{bmatrix}\text{term to account}\\ \text{for larger}\\ \text{numerical}\\ \text{distances}\end{bmatrix} .
$$

Since $|n^2| >> 1$ ($|\Delta^2| << 1$), we can set the function u_1 in the second term of equation (12) equal to γ_1, the propagation constant in the earth. Therefore,

$$
\Delta^2 u_1 \approx \Delta^2\gamma_1 = \gamma_0\Delta \tag{13}
$$

and

$$I_{DIV} \sim 2\Delta^2\left[\frac{e^{-\gamma_0 R_1}}{R_1} - \int_0^\infty \frac{\gamma_0 \Delta e^{-u_0(z+h)}}{u_0(u_0 + \gamma_0\Delta)} J_0(\lambda\rho)\lambda d\lambda\right]$$
$$= 2\Delta^2\left(\frac{e^{-\gamma_0 R_1}}{R_1} - P\right) . \tag{14}$$

Since $|\gamma_0\Delta| << 1$, the integral P will be of importance only when $|\gamma_0 R_1| >> 1$. Wait[10,13] has shown that, when $|n^2| >> 1$ and $|\gamma_0 R_1| >> 1$,

$$P \sim \left(\frac{\Delta}{\sin\psi_1 + \Delta}\right)[1 - F(w)]\frac{e^{-\gamma_0 R_1}}{R_1} , \tag{15}$$

where

$$F(w) \sim 1 - i(\pi w)^{1/2}e^{-w}\operatorname{erfc}(iw^{1/2}) \tag{16}$$

is the Sommerfeld surface-wave attenuation function, $\sin\psi_1 = (z + h)/R_1$, and

$$w \sim -\frac{\gamma_0 R_1}{2}(\sin\psi_1 + \Delta)^2 \tag{17}$$

is the Sommerfeld numerical distance. For small numerical distances $F(w) \sim 1$, while for large numerical distances and negative arguments, $F(w) \sim -1/(2w)$.

For $|n^2| >> 1$, the Fresnel reflection coefficient for vertical polarization reduces to

$$\Gamma_{\shortparallel} \sim \frac{\sin\psi_1 - \Delta}{\sin\psi_1 + \Delta} . \tag{18}$$

Since

$$\frac{1 - \Gamma_{\shortparallel}}{2} = \frac{\Delta}{\sin\psi_1 + \Delta} , \tag{19}$$

equation (15) can be rewritten as

$$P \sim \left(\frac{1 - \Gamma_{\shortparallel}}{2}\right)[1 - F(w)]\frac{e^{-\gamma_0 R_1}}{R_1} . \tag{20}$$

Therefore, from equations (14) and (20),

$$I_{DIV} \sim \frac{2\Delta^2 e^{-\gamma_0 R_1}}{R_1}\left\{1 - \left(\frac{1 - \Gamma_{\shortparallel}}{2}\right)[1 - F(w)]\right\} = \frac{2\Delta^2 A e^{-\gamma_0 R_1}}{R_1} , \tag{21}$$

where

$$A = 1 - \left(\frac{1 - \Gamma_{\shortparallel}}{2}\right)[1 - F(w)]$$
$$= \left(\frac{1 + \Gamma_{\shortparallel}}{2}\right) + \left(\frac{1 - \Gamma_{\shortparallel}}{2}\right)F(w) = \frac{\sin \psi_1 + \Delta F(w)}{\sin \psi_1 + \Delta} \, . \tag{22}$$

Thus, from equations (9) and (21),

$$\vec{\nabla} \cdot \vec{\Pi} - \frac{p \cos \phi}{4\pi i\omega\varepsilon_0} \times \frac{\partial}{\partial\rho}\left(\frac{e^{-\gamma_0 R_0}}{R_0} - \frac{e^{-\gamma_0 R_1}}{R_1} + \frac{2\Delta^2 A e^{-\gamma_0 R_1}}{R_1}\right) . \tag{23}$$

Another factor that we will encounter in the derivation of the field-strength components is the factor B, which is

$$B = \sin \psi_1 - \Delta A = \left(\frac{1 + \Gamma_{\shortparallel}}{2}\right)\sin \psi_1 - \left(\frac{1 - \Gamma_{\shortparallel}}{2}\right)\Delta F(w)$$
$$= \frac{\sin^2 \psi_1 - \Delta^2 F(w)}{\sin \psi_1 + \Delta} \, . \tag{24}$$

For small numerical distances (i.e., $F(w) \sim 1$), $A \sim 1$, and $B \sim \sin \psi_1 - \Delta$. Furthermore, for $\sin \psi_1 >> |\Delta|$, $A \sim 1$ and $B \sim \sin \psi_1$. When $\sin \psi_1$ is comparable to or less than Δ, the horizontal distance ρ will be much greater than the sum of the transmitting and receiving antenna heights $(z + h)$. In the limit as ψ_1 approaches zero, $A \sim F(w_0)$ and $B \sim -\Delta F(w_0)$, where

$$F(w_0) \sim 1 - i(\pi w_0)^{1/2} e^{-w_0} \mathrm{erfc}(i w_0^{1/2}) \tag{25}$$

and

$$w_0 = - \frac{\gamma_0 \rho \Delta^2}{2} \, . \tag{26}$$

For this case (i.e., $\rho^2 >> (z + h)^2$), Wait[10,13] has shown that $F(w)$ can be replaced by

$$F(w) \sim [1 + \gamma_0 \Delta (z + h)] F(w_0) \tag{27}$$

and we can make use of his tabulated results[13] of the function $F(w_0)$.

Since the factor A (equation (22)) is different from unity only when (1) the angle ψ_1 is very small and (2) the Sommerfeld attenuation function $F(w)$ is different from unity, A is only a farfield surface-wave term. Therefore, we can discard all derivatives of A that are not farfield terms. For example, when $|n^2| >> 1$ and $|\Delta \sin \psi_1| << 1$,

$$\frac{\partial}{\partial\rho}\left(\frac{Ae^{-\gamma_0 R_1}}{R_1}\right) = -A(1 + \gamma_0 R_1)\cos\,\psi_1\,\frac{e^{-\gamma_0 R_1}}{R_1^2} + \frac{e^{-\gamma_0 R_1}}{R_1} \times \frac{\partial A}{\partial\rho}$$

$$\sim -A(1 + \gamma_0 R_1)\cos\,\psi_1\,\frac{e^{-\gamma_0 R_1}}{R_1^2} \tag{28}$$

$$\sim -(1 + \gamma_0 R_1 A)\cos\,\psi_1\,\frac{e^{-\gamma_0 R_1}}{R_1^2}\ .$$

Therefore, from equations (23) and (28),

$$\vec{\nabla}\cdot\vec{\Pi} \sim -\frac{p\cos\phi}{4\pi i\omega\varepsilon_0}\left[(1 + \gamma_0 R_0)\cos\,\psi_0\,\frac{e^{-\gamma_0 R_0}}{R_0^2} - (1 + \gamma_0 R_1)\cos\,\psi_1\,\frac{e^{-\gamma_0 R_1}}{R_1^2} + \frac{2\cos\,\psi_1 e^{-\gamma_0 R_1}}{n^2 R_1^2}(1 + \gamma_0 R_1 A)\right]\ , \tag{29}$$

which is identical to equation (39) of Bannister.[9]

From equation (11), utilizing the identity $(u_1 - u_0)(u_1 + u_0) = \gamma_1^2 - \gamma_0^2$, we have

$$\frac{u_1 - u_0}{\gamma_1^2 u_0 + \gamma_0^2 u_1} = \frac{1}{u_0(u_1 + u_0)} - \frac{\Delta^2}{u_0(u_0 + \Delta^2 u_1)}\ . \tag{30}$$

Therefore, equation (2) reduces to

$$\Pi_z = \frac{p\cos\phi}{4\pi i\omega\varepsilon_0} \times \frac{\partial}{\partial\rho}\left[\frac{2e^{-u_0(z+h)}}{u_0(u_1 + u_0)}\,J_0(\lambda\rho)\lambda d\lambda - 2\Delta^2\int_0^\infty \frac{e^{-u_0(z+h)}}{u_0(u_0 + \Delta^2 u_1)}\,J_0(\lambda\rho)\lambda d\lambda\right] \tag{31}$$

$$= \begin{bmatrix}\text{small Sommerfeld numerical}\\ \text{distance term}\end{bmatrix} + \begin{bmatrix}\text{term to account for}\\ \text{larger numerical distances}\end{bmatrix}\ .$$

Equation (31) is equivalent to

$$\Pi_z = \frac{p\cos\phi}{4\pi i\omega\varepsilon_0} \times \frac{\partial}{\partial\rho}(I_{21} - I_{22})\ , \tag{32}$$

where

$$I_{21} = \int_0^\infty \left(\frac{2u_0}{u_1 + u_0}\right)e^{-u_0(z+h)}\,J_0(\lambda\rho)\frac{\lambda}{u_0^2}\,d\lambda \tag{33}$$

and

$$I_{22} = 2\Delta^2 \int_0^\infty \frac{e^{-u_0(z+h)}}{u_0(u_0 + \Delta^2 u_1)} J_0(\lambda\rho)\lambda d\lambda \, . \tag{34}$$

Since

$$\frac{\partial I_{21}}{\partial\rho} = -\int_0^\infty \left(\frac{2u_0}{u_1 + u_0}\right) e^{-u_0(z+h)} J_1(\lambda\rho)\frac{\lambda^2}{u_0^2}\, d\lambda \tag{35}$$

and

$$\frac{2u_0}{u_1 + u_0} = 1 - e^{-u_0 d} \, , \tag{5}$$

then,

$$\frac{\partial I_{21}}{\partial\rho} = -\int_0^\infty \left(1 - e^{-u_0 d}\right) e^{-u_0(z+h)} J_1(\lambda\rho)\frac{\lambda^2}{u_0^2}\, d\lambda \, . \tag{36}$$

Bannister[7,8] has shown that

$$\frac{\partial I_{21}}{\partial\rho} = -\frac{1}{\rho}\left[\sin\psi_2 e^{-\gamma_0 R_2} - (\sin\psi_1 - \gamma_0 d)e^{-\gamma_0 R_1}\right] \, , \tag{37}$$

which, after some manipulation, can also be expressed [utilizing equation (A-8)] as

$$\frac{\partial I_{21}}{\partial\rho} = \frac{\cos\psi_2 e^{-\gamma_0 R_2}}{R_2 + d + z + h} - \frac{(1 + \gamma_0 d)\cos\psi_1 e^{-\gamma_0 R_1}}{R_1 + z + h} \, , \tag{38}$$

where $\sin\psi_1 = (z + h)/R_1$, $\cos\psi_1 = \rho/R_1$, $\sin\psi_2 = (d + z + h)/R_2$, and $\cos\psi_2 = \rho/R_2$.

If we follow the same procedure as in the derivation of $\vec{\nabla} \cdot \vec{\Pi}$, equation (34) reduces to

$$\begin{aligned} I_{22} &= 2\Delta^2 \int_0^\infty \frac{e^{-u_0(z+h)}}{u_0(u_0 + \gamma_0\Delta)} J_0(\lambda\rho)\lambda d\lambda \\ &= \frac{2\Delta^2 P}{\gamma_0\Delta} = \frac{2P}{\gamma_1} = dP \end{aligned} \tag{39}$$

and, retaining only terms in 1/R, we have

$$-\frac{\partial I_{22}}{\partial \rho} \sim \gamma_0 dP \cos\psi_1 = \gamma_0 d \cos\psi_1 \left(\frac{1-\Gamma_{\shortparallel}}{2}\right)[1 - F(w)]\frac{e^{-\gamma_0 R_1}}{R_1} . \tag{40}$$

Therefore, from equations (22), (32), (37), and (40),

$$\begin{aligned}\Pi_z \sim -\frac{p\cos\phi}{4\pi i\omega\varepsilon_0\rho}\Big[&\sin\psi_2 e^{-\gamma_0 R_2} - \sin\psi_1 e^{-\gamma_0 R_1} \\ &+ \gamma_0 d e^{-\gamma_0 R_1}(\sin^2\psi_1 + A\cos^2\psi_1)\Big] .\end{aligned} \tag{41}$$

Since we have now derived expressions for the HED Hertz vector [equations (8), (29), and (41)], the fields in air can be obtained from

$$\begin{aligned}\vec{E} &= -\gamma_0^2\vec{\Pi} + \vec{\nabla}(\vec{\nabla}\cdot\vec{\Pi}) \\ \vec{H} &= i\omega\varepsilon_0(\vec{\nabla}\cdot\vec{\Pi}) .\end{aligned} \tag{42}$$

If we follow the same procedure as outlined above, we also can obtain suitable expressions for the HMD, VED, and VMD Hertz vectors. The resulting HED, HMD, VED, and VMD field-component expressions for the air-to-air propagation case are presented in tables 1 and 2.* They are strictly valid for $|n^2| >> 1$. However, for most cases, the requirement that $|n^2| \geq 10$ is sufficient.

These formulas reduce to the author's previously derived results when either (1) the Sommerfeld numerical distance is small,[7,8] (2) the measurement distance is much less than a free-space wavelength,[1,2] or (3) the measurement distance is much greater than an earth-skin depth.[9] When $\sigma_1 \to \infty$, $d \to 0$, $\Delta \to 0$, $n \to \infty$, $\Gamma_{\shortparallel} \to 1$, $R_2 \to R_1$, $F(w) \to 1$, $A \to 1$ and the formulas reduce to well-known equations for propagation over a perfectly conducting flat earth. For convenience, these equations are listed in tables 3 and 4.

It should be noted that the VED E_z and H_ϕ and HMD E_z field-component expressions presented in tables 1 and 2 were first derived by Norton.[14,15] Also, all VMD components, as well as the HED and HMD H_z components, are identical to the author's previously derived results.[2,7,8] For the sake of convenience, we have tabulated them in this report. In these tables (tables 1 through 4), $\sin\psi_0 = (z - h)/R_0$, $\cos\psi_0 = \rho/R_0$, $\sin\psi_1 = (z + h)/R_1$, $\cos\psi_1 = \rho/R_1$, $\sin\psi_2 = (d + z + h)/R_2$, and $\cos\psi_2 = \rho/R_2$.

*All tables have been placed together at the end of this report.

SURFACE-TO-AIR PROPAGATION

The HED, HMD, VED, and VMD field-component expressions for the surface-to-air propagation case ($h = 0$, $z \geq 0$) can be obtained from the air-to-air propagation equations (tables 1 and 2) simply by setting $h = 0$. The resulting equations are presented in tables 5 and 6. In these tables, $R^2 = \rho^2 + z^2$, $R_i^2 = \rho^2 + (d + z)^2$, $\sin \psi = z/R$, $\cos \psi = \rho/R$, $\sin \psi_i = (d + z)/R_i$, and $\cos \psi_i = \rho/R_i$. These formulas are strictly valid for $|n^2| >> 1$. However, for most cases, the requirement that $|n^2| \geq 10$ is sufficient.

Image-theory expressions for the subsurface-to-air propagation case can be obtained from the surface-to-air propagation equations (tables 5 and 6) simply by multiplying each expression by $\exp(\gamma_1 h)$. (All VED components must also be multiplied by $1/n^2$ to satisfy the boundary conditions.) The resulting formulas will be valid for $|n^2| >> 1$ and $R^2 >> |h|^2$.

AIR-TO-SURFACE PROPAGATION

The HED, HMD, VED, and VMD field-component expressions for the air-to-surface propagation case ($h \geq 0$, $z = 0$) can be obtained from the air-to-air propagation equations (tables 1 and 2) simply by setting $z = 0$. The resulting equations are presented in tables 7 and 8. In these tables $D^2 = \rho^2 + h^2$, $D_i^2 = \rho^2 + (d + h)^2$, $\sin \psi = h/D$, $\cos \psi = \rho/D$, $\sin \psi_i = (d + h)/D_i$, and $\cos \psi_i = \rho/D_i$. These formulas are strictly valid for $|n^2| >> 1$. However, for most cases, the requirement that $|n^2| \geq 10$ is sufficient.

Image-theory expressions for the air-to-subsurface propagation case can be obtained from the air-to-surface propagation equations (tables 7 and 8) simply by multiplying each expression by $\exp(\gamma_1 z)$. (All E_z components must also be multiplied by $1/n^2$ to satisfy the boundary conditions.) The resulting equations will be valid for $|n^2| >> 1$ and $D^2 >> |z|^2$.

SURFACE-TO-SURFACE PROPAGATION

The (simple form) HED, HMD, VED, and VMD field-component expressions for the surface-to-surface propagation case can be obtained from the air-to-air propagation equations (tables 1 and 2) simply by setting both z and h equal to zero. The resulting equations are listed in table 9. In these tables, $\rho_i^2 = \rho^2 + d^2$, $\sin \psi_i = d/\rho_i$, and $\cos \psi_i = \rho/\rho_i$. These formulas are strictly valid for $|n^2| >> 1$. However, for most cases, the requirement that $|n^2| \geq 10$ is sufficient.

It should be noted that the VMD H_ρ (and, by reciprocity, the HMD H_z) image-theory expressions for the surface-to-surface propagation case are only valid when $\rho >> \delta$, where δ is the earth-skin depth. When this condition is not satisfied, other formulas should be utilized for these two field components (for example, see table 9 of Bannister[16]).

Image-theory expressions for the subsurface-to-subsurface propagation case can be obtained from the surface-to-surface propagation equations (table 9) simply by multiplying each expression by $\exp[\gamma_1(z + h)]$. (The VED E_ρ and H_ϕ and the HED and HMD E_z components must be multiplied by $1/n^2$, while the VED E_z component must be multiplied by $1/n^4$, to satisfy the boundary conditions.) The resulting equations will be valid for $|n^2| >> 1$ and $\rho^2 >> |z + h|^2$. It should be noted, however, that more accurate formulas are available for the subsurface-to-subsurface propagation case when $|n^2| >> 1$.[16,17]

CONCLUSIONS

In this report, we have extended the use of finitely conducting earth-image theory techniques to any range and have derived formulas for the electric and magnetic fields produced by the four elementary dipole antennas for the air-to-air, surface-to-air, air-to-surface, and surface-to-surface propagation cases. The only restriction on the use of these formulas is that $|n^2| \geq 10$. They are valid at any frequency and at any range for the flat-earth case. These formulas reduce to the author's previously derived results when either (1) the Sommerfeld numerical distance is small, (2) the measurement distance is much less than a free-space wavelength, or (3) the measurement distance is much greater than an earth-skin depth.

The results presented in this report can be extended to a multilayered earth simply by letting $d = (2/\gamma_1)Q$, where Q is the familiar plane-wave correction factor employed to account for the presence of stratification in the earth.[13] For a homogeneous ground, the argument of the numerical distance w_0 is always between 0 and -90, resulting in the transverse magnetic (TM) surface-wave fields varying as $1/\rho^2$ as $\rho \to \infty$. For a stratified ground, the argument of w_0 can be positive, resulting in the TM surface-wave fields varying as $1/\sqrt{\rho}$.[13]

It should be noted that the two media can be inverted and the air replaced by the earth's crust (of conductivity σ_2 and dielectric constant ε_2). The same equations (tables 1 through 9) can be utilized as long as $|n_2^2| = |\gamma_1^2/\gamma_2^2| \geq 10$ simply by replacing $i\omega\varepsilon_0$ by $\sigma_2 + i\omega\varepsilon_2$.

These formulas are intended to supplement the author's recently derived[9,16] subsurface-to-subsurface and air-to-air propagation formulas. In terms of computer time, the formulas presented in these three reports can be evaluated in fractions of a minute compared with hours for the complete numerical evaluation of the exact Sommerfeld integrals.

Table 1. Electric-Field Air

Dipole Type	E_ρ	
VED	$\frac{p}{4\pi i\omega\epsilon_0}\Big\{(3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2)\sin\psi_0 \cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^3}$ $+ (3 + 3\gamma_0 R_1 + \Gamma_{\shortparallel}\gamma_0^2 R_1^2)\sin\psi_1 \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^3}$ $- \frac{2}{n^2}(3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)\sin\psi_1 \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^3}$ $+ \gamma_0^2\left[\frac{\cos\psi_2 e^{-\gamma_0 R_2}}{R_2 + d + z + h} - \frac{\cos\psi_1 e^{-\gamma_0 R_1}}{R_1 + z + h}(1 + \gamma_0 d)\right]$ $+ 2\Delta\left[1 - \left(\frac{1 - \Gamma_{\shortparallel}}{2}\right)F(w)\right]\cos\psi_1\ \gamma_0^2 R_1^2 \frac{e^{-\gamma_0 R_1}}{R_1^3}\Big\}$	
VMD	0	$-\frac{i\omega\mu_0 m}{4\pi}\Big[($ … $- (1 + \gamma_0$ …

c-Field Air-to-Air Propagation Formulas ($|n^2| \geq 10$)

E_ϕ	E_z
0	$-\frac{p}{4\pi i\omega\varepsilon_0}\left\{[(1 - 3\sin^2\psi_0)(1 + \gamma_0 R_0) + \gamma_0^2 R_0^2 \cos^2\psi_0]\frac{e^{-\gamma_0 R_0}}{R_0^3} + [(1 - 3\sin^2\psi_1)(1 + \gamma_0 R_1) + \Gamma_{\shortparallel}\gamma_0^2 R_1^2 \cos^2\psi_1]\frac{e^{-\gamma_0 R_1}}{R_1^3} + (1 - \Gamma_{\shortparallel})F(w)\cos^2\psi_1(\gamma_0^2 R_1^2)\frac{e^{-\gamma_0 R_1}}{R_1^3}\right\}$
$-\frac{i\omega\mu_0 m}{4\pi}\left[(1 + \gamma_0 R_0)\cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} - (1 + \gamma_0 R_2)\cos\psi_2 \frac{e^{-\gamma_0 R_2}}{R_2^2}\right]$	0

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Table 1. (Cont'd) Electric-F

Dipole Type	E_ρ	
HED	$\frac{p\cos\phi}{4\pi i\omega\varepsilon_0}\Bigg[\Bigg\{(3\cos^2\psi_0 - 1)(1+\gamma_0R_0) - \gamma_0^2R_0^2\sin^2\psi_0\Bigg\}\frac{e^{-\gamma_0R_0}}{R_0^3}$ $- \Bigg\{(3\cos^2\psi_1 - 1)(1+\gamma_0R_1) - \Gamma_{\parallel}\gamma_0^2R_1^2\sin^2\psi_1\Bigg\}\frac{e^{-\gamma_0R_1}}{R_1^3}$ $+ \frac{2e^{-\gamma_0R_1}}{n^2R_1^3}\Bigg\{[(3\cos^2\psi_1-1)(1+\gamma_0R_1)] - \frac{2R_1^2}{d^2}\Bigg[1-\frac{R_1}{R_2}e^{-\gamma_0(R_2-R_1)}\Bigg]$ $+ n^2\gamma_0^2R_1^2\Bigg[\sin\psi_1 + \left(\frac{1-\Gamma_{\parallel}}{2}\right)\Delta F(w)\Bigg]\Bigg\}\Bigg]$	$\frac{p\sin\phi}{4\pi i\omega\varepsilon_0}$ $-(1+\gamma$ $+\frac{2e^{-\gamma_0R}}{n^2R_1^3}$
HMD	$-\frac{i\omega\mu_0 m\cos\phi}{4\pi}\Bigg[(1+\gamma_0R_0)\sin\psi_0\frac{e^{-\gamma_0R_0}}{R_0^2}$ $+(1+\Gamma_{\parallel}\gamma_0R_1)\sin\psi_1\frac{e^{-\gamma_0R_1}}{R_1^2} - d\left(\frac{1-\Gamma_{\parallel}}{2}\right)F(w)\gamma_0^2R_1^2\frac{e^{-\gamma_0R_1}}{R_1^3}$ $+\frac{e^{-\gamma_0R_2}}{R_2(R_2+d+z+h)} - \frac{(1+\gamma_0 d)e^{-\gamma_0R_1}}{R_1(R_1+z+h)}\Bigg]$	$\frac{i\omega\mu_0 m\ \mathrm{si}}{4\pi}$ $+(1+\gamma$ $-\frac{e}{R_2(R_2+}$

Electric-Field Air-to-Air Propagation Formulas ($|n^2| \geq 10$)

E_ϕ	E_z
$\frac{p \sin\phi}{4\pi i\omega\epsilon_0}\left[(1 + \gamma_0 R_0 + \gamma_0^2 R_0^2)\frac{e^{-\gamma_0 R_0}}{R_0^3} - (1 + \gamma_0 R_1 + \gamma_0^2 R_1^2)\frac{e^{-\gamma_0 R_1}}{R_1^3} + \frac{2e^{-\gamma_0 R_1}}{n^2 R_1^3}\left\{(1 + \gamma_0 R_1 A) + \frac{2R_1^2}{d^2}\left[1 - \frac{R_1}{R_2} e^{-\gamma_0 (R_2 - R_1)}\right]\right\}\right]$	$\frac{p \cos\phi}{4\pi i\omega\epsilon_0}\left\{(3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2)\sin\psi_0 \cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^3} - (3 + 3\gamma_0 R_1 + \Gamma_{\shortparallel}\gamma_0^2 R_1^2)\sin\psi_1 \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^3} + \frac{2}{n^2}(3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)\sin\psi_1 \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^3} - \gamma_0^2\left[\frac{\cos\psi_2 e^{-\gamma_0 R_2}}{R_2 + d + z + h} - \frac{\cos\psi_1 e^{-\gamma_0 R_1}}{R_1 + z + h}(1 + \gamma_0 d)\right] - 2\Delta\left[1 - \left(\frac{1 - \Gamma_{\shortparallel}}{2}\right)F(w)\right]\cos\psi_1 (\gamma_0^2 R_1^2)\frac{e^{-\gamma_0 R_1}}{R_1^3}\right\}$
$\frac{i\omega\mu_0 m \sin\phi}{4\pi}\left[(1 + \gamma_0 R_0)\sin\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} + (1 + \gamma_0 R_2)\sin\psi_2 \frac{e^{-\gamma_0 R_2}}{R_2^2} - \frac{e^{-\gamma_0 R_2}}{R_2(R_2 + d + z + h)} + \frac{(1 + \gamma_0 dA)e^{-\gamma_0 R_1}}{R_1(R_1 + z + h)}\right]$	$\frac{i\omega\mu_0 m \cos\phi}{4\pi}\left[(1 + \gamma_0 R_0)\cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} + (1 + \Gamma_{\shortparallel}\gamma_0 R_1)\cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2} + (1 - \Gamma_{\shortparallel})F(w)\cos\psi_1 (\gamma_0 R_1)\frac{e^{-\gamma_0 R_1}}{R_1^2}\right]$

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Table 2. Magnetic-Field

Dipole Type	H_ρ	
VED	0	$\frac{p}{4\pi}\Big[(1 + \gamma_0 R_0)\cos$ $+ (1 - \Gamma_{\parallel})F(w)\cos$
VMD	$\frac{m}{4\pi}\Big[(3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2)\sin\psi_0 \cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^3}$ $- (3 + 3\gamma_0 R_2 + \gamma_0^2 R_2^2)\sin\psi_2 \cos\psi_2 \frac{e^{-\gamma_0 R_2}}{R_2^3}\Big]$	
HED	$\frac{p \sin\phi}{4\pi}\Big[(1 + \gamma_0 R_2)\sin\psi_2 \frac{e^{-\gamma_0 R_2}}{R_2^2}$ $- (1 + \gamma_0 R_0)\sin\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2}$ $- \frac{e^{-\gamma_0 R_2}}{R_2(R_2 + d + z + h)} + \frac{(1 + \gamma_0 dA)e^{-\gamma_0 R_1}}{R_1(R_1 + z + h)}\Big]$	$- \frac{p \cos\phi}{4\pi}\Big[(1 + \gamma_0$ $- (1 + \Gamma_{\parallel}\gamma_0 R_1)\sin$ $- \frac{e^{-\gamma_0 R_2}}{R_2(R_2 + d + z +}$
HMD	$\frac{m \sin\phi}{4\pi}\Big\{[(2 + 2\gamma_0 R_0) - \sin^2\psi_0(3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2)]\frac{e^{-\gamma_0 R_0}}{R_0^3}$ $+ [(2 + 2\gamma_0 R_2 + \gamma_0^2 R_2^2) - \sin^2\psi_2(3 + 3\gamma_0 R_2 + \gamma_0^2 R_2^2)]\frac{e^{-\gamma_0 R_2}}{R_2^3}$ $- [(2 + 2\gamma_0 R_1 + \gamma_0^2 R_1^2) - \sin^2\psi_1(3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)]\frac{e^{-\gamma_0 R_1}}{R_1^3}$ $+ [(2 + 2\gamma_0 R_1 A) - \sin^2\psi_1(3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)]\frac{e^{-\gamma_0 R_1}}{R_1^3}\Big\}$	$- \frac{m \cos\phi}{4\pi}\Big\{(1 + \gamma_0$ $+ [\Gamma_{\parallel} + (1 - \Gamma_{\parallel})F$

c-Field Air-to-Air Propagation Formulas ($|n^2| \geq 10$)

H_ϕ	H_z
$\gamma_0R_0)\cos\psi_0 \frac{e^{-\gamma_0R_0}}{R_0^2} + (1+\Gamma_{\parallel}\gamma_0R_1)\cos\psi_1 \frac{e^{-\gamma_0R_1}}{R_1^2}$ $)F(w)\cos\psi_1(\gamma_0R_1)\frac{e^{-\gamma_0R_1}}{R_1^2}\Big]$	0
0	$-\frac{m}{4\pi}\Big\{[(1+\gamma_0R_0+\gamma_0^2R_0^2) - \sin^2\psi_0(3+3\gamma_0R_0+\gamma_0^2R_0^2)]\frac{e^{-\gamma_0R_0}}{R_0^3}$ $- [(1+\gamma_0R_2+\gamma_0^2R_2^2) - \sin^2\psi_2(3+3\gamma_0R_2+\gamma_0^2R_2^2)]\frac{e^{-\gamma_0R_2}}{R_2^3}\Big\}$
$\phi\Big[(1+\gamma_0R_0)\sin\psi_0 \frac{e^{-\gamma_0R_0}}{R_0^2}$ $\gamma_0R_1)\sin\psi_1 \frac{e^{-\gamma_0R_1}}{R_1^2} + \frac{\gamma_0^2R_1^2 d}{R_1^3}\left(\frac{1-\Gamma_{\parallel}}{2}\right)F(w)e^{-\gamma_0R_1}$ $\frac{e^{-\gamma_0R_2}}{+ d + z + h)} + \frac{(1+\gamma_0 d)}{R_1(R_1+z+h)}e^{-\gamma_0R_1}\Big]$	$\frac{p\sin\phi}{4\pi}\Big[(1+\gamma_0R_0)\cos\psi_0 \frac{e^{-\gamma_0R_0}}{R_0^2}$ $- (1+\gamma_0R_2)\cos\psi_2 \frac{e^{-\gamma_0R_2}}{R_2^2}\Big]$
$\phi\Big\{(1+\gamma_0R_0+\gamma_0^2R_0^2)\frac{e^{-\gamma_0R_0}}{R_0^3} + (1+\gamma_0R_2)\frac{e^{-\gamma_0R_2}}{R_2^3}$ $[1-\Gamma_{\parallel})F(w)]\gamma_0^2R_1^2 \frac{e^{-\gamma_0R_1}}{R_1^3}\Big\}$	$\frac{m\sin\phi}{4\pi}\Big[(3+3\gamma_0R_0+\gamma_0^2R_0^2)\sin\psi_0\cos\psi_0 \frac{e^{-\gamma_0R_0}}{R_0^3}$ $+ (3+3\gamma_0R_2+\gamma_0^2R_2^2)\sin\psi_2\cos\psi_2 \frac{e^{-\gamma_0R_2}}{R_2^3}\Big]$

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Table 3. Electric-Fiel

Dipole Type	E_ρ
VED	$\frac{p}{4\pi i\omega\epsilon_0}\left[(3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2)\sin\psi_0 \cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^3} + (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)\sin\psi_1 \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^3}\right]$
VMD	0
HED	$\frac{p \cos\phi}{4\pi i\omega\epsilon_0}\left\{[(2 + 2\gamma_0 R_0) - \sin^2\psi_0(3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2)]\frac{e^{-\gamma_0 R_0}}{R_0^3} - [(2 + 2\gamma_0 R_1) - \sin^2\psi_1(3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)]\frac{e^{-\gamma_0 R_1}}{R_1^3}\right\}$
HMD	$-\frac{i\omega\mu_0 m \cos\phi}{4\pi}\left[(1 + \gamma_0 R_0)\sin\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} + (1 + \gamma_0 R_1)\sin\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}\right]$

E-Field Air-to-Air Propagation Formulas for $\sigma_1 \to \infty$

E_ϕ	E_z
0	$-\frac{p}{4\pi i\omega\varepsilon_0}\left\{[(1+\gamma_0R_0+\gamma_0^2R_0^2)-\sin^2\psi_0(3+3\gamma_0R_0+\gamma_0^2R_0^2)]\frac{e^{-\gamma_0R_0}}{R_0^3}+[(1+\gamma_0R_1+\gamma_0^2R_1^2)-\sin^2\psi_1(3+3\gamma_0R_1+\gamma_0^2R_1^2)]\frac{e^{-\gamma_0R_1}}{R_1^3}\right\}$
$-\frac{i\omega\mu_0 m}{4\pi}\left[(1+\gamma_0R_0)\cos\psi_0\,\frac{e^{-\gamma_0R_0}}{R_0^2}-(1+\gamma_0R_1)\cos\psi_1\,\frac{e^{-\gamma_0R_1}}{R_1^2}\right]$	0
$\frac{p\sin\phi}{4\pi i\omega\varepsilon_0}\left[(1+\gamma_0R_0+\gamma_0^2R_0^2)\frac{e^{-\gamma_0R_0}}{R_0^3}-(1+\gamma_0R_1+\gamma_0^2R_1^2)\frac{e^{-\gamma_0R_1}}{R_1^3}\right]$	$\frac{p\cos\phi}{4\pi i\omega\varepsilon_0}\left[(3+3\gamma_0R_0+\gamma_0^2R_0^2)\sin\psi_0\cos\psi_0\,\frac{e^{-\gamma_0R_0}}{R_0^3}-(3+3\gamma_0R_1+\gamma_0^2R_1^2)\sin\psi_1\cos\psi_1\,\frac{e^{-\gamma_0R_1}}{R_1^3}\right]$
$\frac{i\omega\mu_0 m\sin\phi}{4\pi}\left[(1+\gamma_0R_0)\sin\psi_0\,\frac{e^{-\gamma_0R_0}}{R_0^2}+(1+\gamma_0R_1)\sin\psi_1\,\frac{e^{-\gamma_0R_1}}{R_1^2}\right]$	$\frac{i\omega\mu_0 m\cos\phi}{4\pi}\left[(1+\gamma_0R_0)\cos\psi_0\,\frac{e^{-\gamma_0R_0}}{R_0^2}+(1+\gamma_0R_1)\cos\psi_1\,\frac{e^{-\gamma_0R_1}}{R_1^2}\right]$

Table 4. Magnetic-Fi

Dipole Type	H_ρ	
VED	0	$\frac{p}{4\pi}$ + (
VMD	$\frac{m}{4\pi}\left[(3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2)\sin\psi_0 \cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^3} - (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)\sin\psi_1 \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^3}\right]$	
HED	$-\frac{p\sin\phi}{4\pi}\left[(1 + \gamma_0 R_0)\sin\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} - (1 + \gamma_0 R_1)\sin\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}\right]$	− I − (
HMD	$\frac{m\sin\phi}{4\pi}\left\{[(2 + 2\gamma_0 R_0) - \sin^2\psi_0(3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2)]\frac{e^{-\gamma_0 R_0}}{R_0^3} + [(2 + 2\gamma_0 R_1) - \sin^2\psi_1(3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)]\frac{e^{-\gamma_0 R_1}}{R_1^3}\right]$	− m + (

netic-Field Air-to-Air Propagation Formulas for $\sigma_1 \to \infty$

	H_ϕ	H_z
	$\frac{p}{4\pi}\left[(1 + \gamma_0 R_0)\cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} + (1 + \gamma_0 R_1)\cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}\right]$	0
	0	$-\frac{m}{4\pi}\left\{[(1 + \gamma_0 R_0 + \gamma_0^2 R_0^2) - \sin^2\psi_0(3 + 3\gamma_0 R_0 + \quad \frac{e^{-\gamma_0 R_0}}{R_0^3} - [(1 + \gamma_0 R_1 + \gamma_0^2 R_1^2) - \sin^2\psi_1(3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)]\frac{e^{-\gamma_0 R_1}}{R_1^3}\right\}$
	$-\frac{p\cos\phi}{4\pi}\left[(1 + \gamma_0 R_0)\sin\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} - (1 + \gamma_0 R_1)\sin\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}\right]$	$\frac{p\sin\phi}{4\pi}\left[(1 + \gamma_0 R_0)\cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^2} - (1 + \gamma_0 R_1)\cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2}\right]$
	$-\frac{m\cos\phi}{4\pi}\left[(1 + \gamma_0 R_0 + \gamma_0^2 R_0^2)\frac{e^{-\gamma_0 R_0}}{R_0^3} + (1 + \gamma_0 R_1 + \gamma_0 R_1^2)\frac{e^{-\gamma_0 R_1}}{R_1^3}\right]$	$\frac{m\sin\phi}{4\pi}\left[(3 + 3\gamma_0 R_0 + \gamma_0^2 R_0^2)\sin\psi_0 \cos\psi_0 \frac{e^{-\gamma_0 R_0}}{R_0^3} + (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2)\sin\psi_1 \cos\psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^3}\right]$

Table 5. Electric-Field Surface-to-Air Propagat

Dipole Type	E_ρ	
VED	$$\frac{p\cos\psi e^{-\gamma_0 R}}{2\pi i\omega\epsilon_0 R^3}\left[(3+3\gamma_0 R)\sin\psi + \gamma_0^2 R^2 B - \Delta\gamma_0 R\right.$$ $$\left.\times\left\{\frac{R^3 e^{+\gamma_0 R}}{d}\left[\frac{(1+\gamma_0 d)e^{-\gamma_0 R}}{R(R+z)} - \frac{e^{-\gamma_0 R_i}}{R_i(R_i+d+z)}\right] - \gamma_0 R\right\}\right]$$	
VMD	0	$-\frac{i\omega\mu_0}{4\pi}$ $-(1+$
HED	$$\frac{p\cos\phi e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3}\left\{(3\cos^2\psi - 1)(1+\gamma_0 R)\right.$$ $$\left.-\frac{2R^2}{d^2}\left[1 - \frac{R}{R_i}e^{-\gamma_0(R_i - R)}\right] + n\gamma_0^2 R^2(\sin\psi - B)\right\}$$	$\frac{p \sin}{2\pi(\sigma_1 +}$ $+\frac{2R^2}{d^2}\Big[1$
HMD	$$\frac{\gamma_1 m\cos\phi e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3}\left\{-\gamma_1 R\sin\psi - \gamma_0^2 R^2 nB\right.$$ $$\left.+\frac{R^3 e^{+\gamma_0 R}}{d}\left[\frac{(1+\gamma_0 d)e^{-\gamma_0 R}}{R(R+z)} - \frac{e^{-\gamma_0 R_i}}{R_i(R_i+d+z)}\right]\right\}$$	$\frac{i\omega\mu_0 m \text{ si}}{4\pi}$ $+(1+\gamma$ $+\frac{(1+\gamma}{R(}$

to-Air Propagation Formulas ($|n^2| \geq 10$), [$R^2 = \rho^2 + z^2$, $R_i^2 = \rho^2 + (d + z)^2$]

E_ϕ	E_z
0	$-\dfrac{pe^{-\gamma_0 R}}{2\pi i\omega\epsilon R^3}[(1 - 3\sin^2\psi)(1 + \gamma_0 R) + \gamma_0^2 R^2 A \cos^2\psi]$
$-\dfrac{i\omega\mu_0}{4\pi}\left[(1 + \gamma_0 R)\cos\psi\, \dfrac{e^{-\gamma_0 R}}{R^2} - (1 + \gamma_0 R_i)\cos\psi_i\, \dfrac{e^{-\gamma_0 R_i}}{R_i^2}\right]$	0
$\dfrac{p \sin\phi e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^3}\left\{(1 + \gamma_0 RA) + \dfrac{2R^2}{d^2}\left[1 - \dfrac{R}{R_i} e^{-\gamma_0(R_i - R)}\right]\right\}$	$\dfrac{\gamma_1 p \cos\phi \cos\psi e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^2}\left[\gamma_0 RA + \left\{\dfrac{R^3 e^{+\gamma_0 R}}{d} \times \left[\dfrac{(1 + \gamma_0 d)e^{-\gamma_0 R}}{R(R + z)} - \dfrac{e^{-\gamma_0 R_i}}{R_i(R_i + d + z)}\right] - \gamma_0 R\right\}\right]$
$\dfrac{i\omega\mu_0 m \sin\phi}{4\pi}\left[(1 + \gamma_0 R)\sin\psi\, \dfrac{e^{-\gamma_0 R}}{R^2} + (1 + \gamma_0 R_i)\sin\psi_i\, \dfrac{e^{-\gamma_0 R_i}}{R_i^2} + \dfrac{(1 + \gamma_0 dA)e^{-\gamma_0 R}}{R(R + z)} - \dfrac{e^{-\gamma_0 R_i}}{R_i(R_i + d + z)}\right]$	$\dfrac{\gamma_1^2 m \cos\phi \cos\psi e^{-\gamma_0 R}}{2\pi(\sigma_1 + i\omega\epsilon_1)R^2}(1 + \gamma_0 RA)$

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Table 6. Magnetic-Field Surface-to-Air Propagation F

Dipole Type	H_ρ	
VED	0	$\frac{p \cos \psi e^{-\gamma_0 R}}{2\pi R^2}(1$
VMD	$\frac{m}{4\pi}\Big[(3 + 3\gamma_0 R + \gamma_0^2 R^2)\sin\psi\cos\psi\,\frac{e^{-\gamma_0 R}}{R^3}$ $- (3 + 3\gamma_0 R_i + \gamma_0^2 R_i^2)\sin\psi_i\cos\psi_i\,\frac{e^{-\gamma_0 R_i}}{R_i^3}\Big]$	
HED	$\frac{p \sin\phi}{4\pi}\Big[(1 + \gamma_0 R_i)\sin\psi_i\,\frac{e^{-\gamma_0 R_i}}{R_i^2}$ $- (1 + \gamma_0 R)\sin\psi\,\frac{e^{-\gamma_0 R}}{R^2}$ $+ \frac{(1 + \gamma_0 dA)e^{-\gamma_0 R}}{R(R + z)} - \frac{e^{-\gamma_0 R_i}}{R_i(R_i + d + z)}\Big]$	$-\frac{p \cos\phi e^{-\gamma_0 R}}{2\pi\gamma_1 R^3}$ $+\Big[\frac{(1 + \gamma_0 d)e^{-\gamma}}{R(R + z)}$
HMD	$\frac{m \sin\phi}{4\pi}\Big\{\frac{2e^{-\gamma_0 R}}{R^3}[2 + \gamma_0 R(1 + A) - \sin^2\psi(3 + 3\gamma_0 R + \gamma_0^2 R^2)]$ $+ [(2 + 2\gamma_0 R_i + \gamma_0^2 R_i^2) - \sin^2\psi_i(3 + 3\gamma_0 R_i + \gamma_0^2 R_i^2)]\frac{e^{-\gamma_0 R_i}}{R_i^3}$ $- [(2 + 2\gamma_0 R + \gamma_0^2 R^2) - \sin^2\psi(3 + 3\gamma_0 R + \gamma_0^2 R^2)]\frac{e^{-\gamma_0 R}}{R^3}\Big\}$	$-\frac{m \cos\phi}{4\pi}\Big[(1 +$ $+ (1 + \gamma_0 R_i)e^{-\gamma}$

-to-Air Propagation Formulas ($|n^2| \geq 10$), [$R^2 = \rho^2 + z^2$, $R_i^2 = \rho^2 + (d + z)^2$]

	H_ϕ	H_z
	$\frac{p \cos \psi e^{-\gamma_0 R}}{2\pi R^2}(1 + \gamma_0 RA)$	0
	0	$-\frac{m}{4\pi}\left\{[(1 + \gamma_0 R + \gamma_0^2 R^2) - \sin^2 \psi(3 + 3\gamma_0 R + \gamma_0^2 R^2) \frac{e^{-\gamma_0 R}}{R^3} - [(1 + \gamma_0 R_i + \gamma_0^2 R_i^2) - \sin^2 \psi_i (3 + 3\gamma_0 R_i + \gamma_0^2 R_i^2)]\frac{e^{-\gamma_0 R_i}}{R_i^3}\right\}$
	$-\frac{p \cos \phi e^{-\gamma_0 R}}{2\pi\gamma_1 R^3}\left\{\gamma_0^2 R^2 A + \left[\frac{(1 + \gamma_0 d)e^{-\gamma_0 R}}{R(R + z)} - \frac{e^{-\gamma_0 R_i}}{R_i(R_i + d + z)}\right]\right\}$	$\frac{p \sin \phi}{4\pi}\left[(1 + \gamma_0 R)\cos \psi \frac{e^{-\gamma_0 R}}{R^2} - (1 + \gamma_0 R_i)\cos \psi_i \frac{e^{-\gamma_0 R_i}}{R_i^2}\right]$
	$-\frac{m \cos \phi}{4\pi}\left[(1 + \gamma_0 R + 2A\gamma_0^2 R^2)\frac{e^{-\gamma_0 R}}{R^3} + (1 + \gamma_0 R_i)\frac{e^{-\gamma_0 R_i}}{R_i^3}\right]$	$\frac{m \sin \phi}{4\pi}\left[(3 + 3\gamma_0 R + \gamma_0^2 R^2)\sin \psi \cos \psi \frac{e^{-\gamma_0 R}}{R^3} + (3 + 3\gamma_0 R_i + \gamma_0^2 R_i^2)\sin \psi_i \cos \psi_i \frac{e^{-\gamma_0 R_i}}{R_i^3}\right]$

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Table 7. Electric-Field Air-to-Surface Propagatio

Dipole Type	E_ρ	
VED	$-\dfrac{\gamma_1 p \cos\psi e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\varepsilon_1)D^2}\Bigg\{\gamma_0 DA + \dfrac{\sin\psi}{\gamma_1 D}(3 + 3\gamma_0 D + \gamma_0^2 D^2)$ $+ \dfrac{D^3 e^{+\gamma_0 D}}{d}\left[\dfrac{(1 + \gamma_0 d)e^{-\gamma_0 D}}{D(D + h)} - \dfrac{e^{-\gamma_0 D_i}}{D_i(D_i + d + h)}\right] - \gamma_0 D\Bigg\}$	
VMD	0	$-\dfrac{i\omega\mu_0 m}{4\pi}\Big[(1 + \gamma_0$ $- (1 + \gamma_0 D_i)\cos$
HED	$\dfrac{p \cos\phi e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\varepsilon_1)D^3}\Bigg\{(3\cos^2\psi - 1)(1 + \gamma_0 D)$ $- \dfrac{2D^2}{d^2}\left[1 - \dfrac{D}{D_i}e^{-\gamma_0(D_i - D)}\right] + n\gamma_0^2 R^2(\sin\psi - B)\Bigg\}$	$\dfrac{p \sin\phi e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\varepsilon_1)D^3}$ $-\dfrac{2D^2}{d^2}\Big[1 - \dfrac{D}{D_i}e^{-}$
HMD	$\dfrac{\gamma_1 m \cos\phi e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\varepsilon_1)D^3}\Bigg\{\gamma_0^2 D^2 A$ $+ \dfrac{D^3 e^{+\gamma_0 D}}{d}\left[\dfrac{(1 + \gamma_0 d)e^{-\gamma_0 D}}{D(D + h)} - \dfrac{e^{-\gamma_0 D_i}}{D_i(D_i + d + h)}\right]\Bigg\}$	$\dfrac{i\omega\mu_0 m \sin\phi}{4\pi}\Big[(1$ $- (1 + \gamma_0 D)\sin$ $+ \dfrac{(1 + \gamma_0 dA)e^{-\gamma}}{D(D + h)}$

rface Propagation Formulas ($|n^2| \geq 10$), [$D^2 = \rho^2 + h^2$, $D_i^2 = \rho^2 + (d + h)^2$]

E_ϕ	E_z
0	$-\dfrac{pe^{-\gamma_0 D}}{2\pi i\omega\varepsilon_0 D^3}[(1 - 3\sin^2\psi)(1 + \gamma_0 D)$ $+ \gamma_0^2 D^2 A \cos^2\psi]$
$-\dfrac{i\omega\mu_0 m}{4\pi}\left[(1 + \gamma_0 D)\cos\psi\,\dfrac{e^{-\gamma_0 D}}{D^2}\right.$ $\left.- (1 + \gamma_0 D_i)\cos\psi_i\,\dfrac{e^{-\gamma_0 D_i}}{D_i^2}\right]$	0
$\dfrac{p\sin\phi e^{-\gamma_0 D}}{2\pi(\sigma_1 + i\omega\varepsilon_1)D^3}\left\{(1 + \gamma_0 DA)\right.$ $\left.- \dfrac{2D^2}{d^2}\left[1 - \dfrac{D}{D_i}e^{-\gamma_0(D_i - D)}\right]\right\}$	$-\dfrac{p\cos\phi\cos\psi e^{-\gamma_0 D}}{2\pi i\omega\varepsilon_0 D^3}\left[(3 + 3\gamma_0 D)\sin\psi + \gamma_0^2 D^2 B\right.$ $\left.- \Delta\gamma_0 D\left\{\dfrac{De^{+\gamma_0 D}}{d}\left[\dfrac{(1 + \gamma_0 d)e^{-\gamma_0 D}}{D(D + h)} - \dfrac{e^{-\gamma_0 D_i}}{D_i(D_i + d + h)}\right] - \gamma_0 D\right\}\right]$
$\dfrac{i\omega\mu_0 m\sin\phi}{4\pi}\left[(1 + \gamma_0 D_i)\sin\psi_i\,\dfrac{e^{-\gamma_0 D_i}}{D_i^2}\right.$ $- (1 + \gamma_0 D)\sin\psi\,\dfrac{e^{-\gamma_0 D}}{D^2}$ $\left.+ \dfrac{(1 + \gamma_0 dA)e^{-\gamma_0 D}}{D(D + h)} - \dfrac{e^{-\gamma_0 D_i}}{D_i(D_i + d + h)}\right]$	$\dfrac{i\omega\mu_0 m\cos\phi\cos\psi e^{-\gamma_0 D}}{2\pi D^2}(1 + \gamma_0 DA)$

2

1

Table 8. Magnetic-Field Air-to-Surface Propaga

Dipole Type	H_ρ	
VED	0	$\frac{p \cos \psi e^{-\gamma_0 D}}{2\pi D^2}(1$
VMD	$-\frac{m}{4\pi}\Bigg[(3 + 3\gamma_0 D + \gamma_0^2 D^2)\sin\psi\cos\psi\,\frac{e^{-\gamma_0 D}}{D^3}$ $+ (3 + 3\gamma_0 D_i + \gamma_0^2 D_i^2)\sin\psi_i\cos\psi_i\,\frac{e^{-\gamma_0 D_i}}{D_i^3}\Bigg]$	
HED	$\frac{p\sin\phi}{4\pi}\Bigg[(1 + \gamma_0 D)\sin\psi\,\frac{e^{-\gamma_0 D}}{D^2}$ $+ (1 + \gamma_0 D_i)\sin\psi_i\,\frac{e^{-\gamma_0 D_i}}{D_i^2}$ $+ \frac{(1 + \gamma_0 dA)e^{-\gamma_0 D}}{D(D + h)} - \frac{e^{-\gamma_0 D_i}}{D_i(D_i + d + h)}\Bigg]$	$-\frac{p \cos \phi e^{-\gamma_0 D}}{2\pi\gamma_1 D^3}\Big[$ $- \gamma_1 D \sin\psi - \gamma$
HMD	$\frac{m\sin\phi}{4\pi}\Bigg\{\frac{2e^{-\gamma_0 D}}{D^3}[2 + \gamma_0 D(1 + A) - \sin^2\psi(3 + 3\gamma_0 D + \gamma_0^2 D^2)]$ $+ [(2 + 2\gamma_0 D_i + \gamma_0^2 D_i^2) - \sin^2\psi_i(3 + 3\gamma_0 D_i + \gamma_0^2 D_i^2)]\frac{e^{-\gamma_0 D_i}}{D_i^3}$ $- [(2 + 2\gamma_0 D + \gamma_0^2 D^2) - \sin^2\psi(3 + 3\gamma_0 D + \gamma_0^2 D^2)]\frac{e^{-\gamma_0 D}}{D^3}\Bigg\}$	$-\frac{m\cos\phi}{4\pi}\Big[(1 + \gamma$

ce Propagation Formulas ($|n^2| \geq 10$), [$D^2 = \rho^2 + h^2$, $D_i^2 = \rho^2 + (d + h)^2$]

H_ϕ	H_z
[illegible] $\frac{\psi e^{-\gamma_0 D}}{D^2}(1 + \gamma_0 DA)$	0
0	$-\frac{m}{4\pi}\left\{\left[(1 + \gamma_0 D + \gamma_0^2 D^2) - \sin^2 \psi (3 + 3\gamma_0 D + \gamma_0^2 D^2)\right]\frac{e^{-\gamma_0 D}}{D^3} - \left[(1 + \gamma_0 D_i + \gamma_0^2 D_i^2) - \sin^2 \psi_i (3 + 3\gamma_0 D_i + \gamma_0^2 D_i^2)\right]\frac{e^{-\gamma_0 D_i}}{D_i^3}\right\}$
[illegible] $\frac{s\ \phi e^{-\gamma_0 D}}{\gamma_1 D^3}\left\{\frac{D^3 e^{+\gamma_0 D}}{d}\left[\frac{(1 + \gamma_0 d)e^{-\gamma_0 D}}{D(D + h)} - \frac{e^{-\gamma_0 D_i}}{D_i(D + d + h)}\right] \sin \psi - \gamma_0^2 D^2 nB\right\}$	$\frac{p \sin \phi}{4\pi}\left[(1 + \gamma_0 D)\cos \psi \frac{e^{-\gamma_0 D}}{D^2} - (1 + \gamma_0 D_i)\cos \psi_i \frac{e^{-\gamma_0 D_i}}{D_i^2}\right]$
[illegible] $\phi\left[(1 + \gamma_0 D + 2A\gamma_0^2 D^2)\frac{e^{-\gamma_0 D}}{D^3} + (1 + \gamma_0 D_i)\frac{e^{-\gamma_0 D_i}}{D_i^3}\right]$	$-\frac{m \sin \phi}{4\pi}\left[(3 + 3\gamma_0 D + \gamma_0^2 D^2)\sin \psi \cos \psi \frac{e^{-\gamma_0 D}}{D^3} - (3 + 3\gamma_0 D_i + \gamma_0^2 D_i^2)\sin \psi_i \cos \psi_i \frac{e^{-\gamma_0 D_i}}{D_i^3}\right]$

1 2

Table 9. Surface-to-Surface Propagat

Dipole Type	E_ρ	E_ϕ	E_z
VED	$-\dfrac{\gamma_1 p e^{-\gamma_0\rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^2}\left[\dfrac{\rho}{\rho_i} e^{-\gamma_0(\rho_i-\rho)} + \gamma_0\rho F(w_0)\right]$	0	$-\dfrac{p e^{-\gamma_0\rho}}{2\pi i\omega\epsilon_0\rho^3}[1 + \gamma_0\rho + \gamma_0^2\rho^2$
VMD	0	$-\dfrac{i\omega\mu_0 m}{4\pi}\left[(1 + \gamma_0\rho)\dfrac{e^{-\gamma_0\rho}}{\rho^2} - (1 + \gamma_0\rho_i)\cos\phi_i\,\dfrac{e^{-\gamma_0\rho_i}}{\rho_i^2}\right]$	0
HED	$\dfrac{p\cos\phi e^{-\gamma_0\rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3}\left\{2(1 + \gamma_0\rho) + \gamma_0^2\rho^2F(w_0) - \dfrac{2\rho^2}{d^2}\left[1 - \dfrac{\rho}{\rho_i}e^{-\gamma_0(\rho_i-\rho)}\right]\right\}$	$\dfrac{p\sin\phi e^{-\gamma_0\rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3}\left\{[1 + \gamma_0\rho F(w_0)] + \dfrac{2\rho^2}{d^2}\left[1 - \dfrac{\rho}{\rho_i}e^{-\gamma_0(\rho_i-\rho)}\right]\right\}$	$\dfrac{\gamma_1 p\cos\phi e^{-\gamma_0\rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^2}[\dfrac{\rho}{\rho_i} e^{-\gamma_0(\rho_i}$ $+ \gamma_0\rho F(w_0)]$
HMD	$\dfrac{\gamma_1 m\cos\phi e^{-\gamma_0\rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3}\left[\dfrac{\rho}{\rho_i}e^{-\gamma_0(\rho_i-\rho)} + \gamma_0\rho + \gamma_0^2\rho^2F(w_0)\right]$	$\dfrac{\gamma_1 m\sin\phi e^{-\gamma_0\rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3}\left\{\gamma_0\rho F(w_0) + \dfrac{\rho}{\rho_i}\left[1 + \left(\dfrac{\rho}{\rho_i}\right)^2(1 + \gamma_0\rho_i)\right]e^{-\gamma_0(\rho_i-\rho)}\right\}$	$\dfrac{\gamma_1^2 m\cos\phi e^{-\gamma_0\rho}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^2}[1 + \gamma_0\rho F(w$

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ropagation Formulas ($|n^2| \geq 10$), ($\rho_i^2 = \rho^2 + d^2$, $\cos \psi_i = \rho/\rho_i$, $\sin \psi_i = d/\rho_i$)

	H_ρ	H_ϕ	H_z
$+ \gamma_0^2\rho^2F(w_0)]$	0	$\frac{pe^{-\gamma_0\rho}}{2\pi\rho^2}[1 + \gamma_0\rho F(w_0)]$	0
	$-\frac{m \sin \psi_i \cos \psi_i e^{-\gamma_0\rho_i}}{4\pi\rho_i^3}(3 + 3\gamma_0\rho_i + \gamma_0^2\rho_i^2)$	0	$-\frac{m}{4\pi}\left[(1 + \gamma_0\rho + \gamma_0^2\rho^2)\frac{e^{-\gamma_0\rho}}{\rho^3} - (1 + \gamma_0\rho_i + \gamma_0^2\rho_i^2)\frac{e^{-\gamma_0\rho_i}}{\rho_i^3}\right]$
$\frac{\rho}{\rho_i} e^{-\gamma_0(\rho_i-\rho)}$	$\frac{p \sin \phi e^{-\gamma_0\rho}}{2\pi\gamma_1\rho^3}\left\{\gamma_0\rho F(w_0) + \frac{\rho}{\rho_i}\left[1 + \left(\frac{\rho}{\rho_i}\right)^2(1 + \gamma_0\rho_i)\right] e^{-\gamma_0(\rho_i-\rho)}\right\}$	$-\frac{p \cos \phi e^{-\gamma_0\rho}}{2\pi\gamma_1\rho^3}\left[\frac{\rho}{\rho_i} e^{-\gamma_0(\rho_i-\rho)} + \gamma_0\rho + \gamma_0^2\rho^2F(w_0)\right]$	$\frac{p \sin \phi}{4\pi}\left[(1 + \gamma_0\rho)\frac{e^{-\gamma_0\rho}}{\rho^2} - (1 + \gamma_0\rho_i)\cos \psi_i \frac{e^{-\gamma_0\rho_i}}{\rho_i^2}\right]$
$+ \gamma_0\rho F(w_0)]$	$\frac{m \sin \phi}{4\pi}\left\{[2 + 2\gamma_0\rho F(w_0) - \gamma_0^2\rho^2]\frac{e^{-\gamma_0\rho}}{\rho^3} + [(2 - 3 \sin^2 \psi_i)(1 + \gamma_0\rho_i) + \gamma_0^2\rho_i^2]\frac{e^{-\gamma_0\rho_i}}{\rho_i^3}\right\}$	$-\frac{m \cos \phi}{4\pi}\left\{[1 + \gamma_0\rho + 2\gamma_0^2\rho^2F(w_0)]\frac{e^{-\gamma_0\rho}}{\rho^3} + (1 + \gamma_0\rho_i)\frac{e^{-\gamma_0\rho_i}}{\rho_i^3}\right\}$	$\frac{m \sin \phi \sin \psi_i \cos \psi_i}{4\pi\rho_i^3}(3 + 3\gamma_0\rho_i + \gamma_0^2\rho_i^2)e^{-\gamma}$

Reverse

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Appendix

USEFUL APPROXIMATIONS WHEN $R_1 >> |d|$

$$\frac{R_1}{R_2} \simeq 1 - \frac{d^2}{2R_1^2}\left(1 + \frac{2R_1 \sin \psi_1}{d} - 3 \sin^2 \psi_1\right) \tag{A-1}$$

$$\left(\frac{R_1}{R_2}\right)^2 \simeq 1 - \frac{d^2}{R_1^2}\left(1 + \frac{2R_1 \sin \psi_1}{d} - 4 \sin^2 \psi_1\right) \tag{A-2}$$

$$\left(\frac{R_1}{R_2}\right)^3 \simeq 1 - \frac{3d^2}{2R_1^2}\left(1 + \frac{2R_1 \sin \psi_1}{d} - 5 \sin^2 \psi_1\right) \tag{A-3}$$

$$\left(\frac{R_1}{R_2}\right)^4 \simeq 1 - \frac{2d^2}{R_1^2}\left(1 + \frac{2R_1 \sin \psi_1}{d} - 6 \sin^2 \psi_1\right) \tag{A-4}$$

$$\left(\frac{R_1}{R_2}\right)^5 \simeq 1 - \frac{5d^2}{2R_1^2}\left(1 + \frac{2R_1 \sin \psi_1}{d} - 7 \sin^2 \psi_1\right) \tag{A-5}$$

and

$$e^{-\gamma_0(R_2-R_1)} \simeq 1 - \gamma_0 R_1 d\left(\frac{\sin \psi_1}{R_1} + \frac{d \cos^2 \psi_1}{2R_1^2}\right) + \frac{\gamma_0^2 R_1^2 d^2 \sin^2 \psi_1}{2R_1^2} . \tag{A-6}$$

For $|\gamma_1(z + h)| >> 1$ (i.e., $|2(R_1/d)\sin \psi_1| >> 1$),

$$\left(\frac{R_1}{R_2}\right)^x \simeq 1 - \frac{xd \sin \psi_1}{R_1} \tag{A-7}$$

and

$$e^{-\gamma_0(R_2-R_1)} \simeq 1 - \gamma_0 R_1\left(\frac{d \sin \psi_1}{R_1}\right) . \tag{A-8}$$

Some other useful approximations are

$$\frac{\cos \psi_2 e^{-\gamma_0 R_2}}{R_2 + d + z + h} - \frac{(1 + \gamma_0 d)\cos \psi_1 e^{-\gamma_0 R_1}}{R_1 + z + h} \simeq - d \cos \psi_1 (1 + \gamma_0 R_1)\frac{e^{-\gamma_0 R_1}}{R_1^2} \tag{A-9}$$

$$- \left[\frac{e^{-\gamma_0 R_2}}{R_2(R_2 + d + z + h)} - \frac{(1 + \gamma_0 d) e^{-\gamma_0 R_1}}{R_1(R_1 + z + h)} \right] \approx d(1 + \gamma_0 R_1) \frac{e^{-\gamma_0 R_1}}{R_1^3} \tag{A-10}$$

$$- \left[\frac{e^{-\gamma_0 R_2}}{R_2(R_2 + d + z + h)} - \frac{(1 + \gamma_0 dA) e^{-\gamma_0 R_1}}{R_1(R_1 + z + h)} \right] \approx d(1 + \gamma_0 R_1 A) \frac{e^{-\gamma_0 R_1}}{R_1^3} \tag{A-11}$$

$$\begin{aligned} \frac{2R_1^2}{d^2} \left[1 - \frac{R_1}{R_2} e^{-\gamma_0 (R_2 - R_1)} \right] &\approx (1 + \gamma_1 R_1 \sin \psi_1)(1 + \gamma_0 R_1) \\ &\quad - \sin^2 \psi_1 (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2) \end{aligned} \tag{A-12}$$

$$\begin{aligned} (1 + \gamma_0 R_2) \sin \psi_2 \frac{e^{-\gamma_0 R_2}}{R_2^2} &- (1 + \gamma_0 R_1) \sin \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2} \\ &\approx \frac{d e^{-\gamma_0 R_1}}{R_1^3} \left[(1 + \gamma_0 R_1) - \sin^2 \psi_1 (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2) \right] \end{aligned} \tag{A-13}$$

and

$$\begin{aligned} (1 + \gamma_0 R_2) \cos \psi_2 \frac{e^{-\gamma_0 R_2}}{R_2^2} &- (1 + \gamma_0 R_1) \cos \psi_1 \frac{e^{-\gamma_0 R_1}}{R_1^2} \\ &\approx - \frac{d \sin \psi_1 \cos \psi_1 e^{-\gamma_0 R_1}}{R_1^3} (3 + 3\gamma_0 R_1 + \gamma_0^2 R_1^2) \; , \end{aligned} \tag{A-14}$$

where

$R_1^2 = \rho^2 + (z + h)^2$,

$R_2^2 = \rho^2 + (d + z + h)^2$,

$\sin \psi_1 = (z + h)/R_1$,

$\cos \psi_1 = \rho/R_1$,

$\sin \psi_2 = (d + z + h)/R_2$, and

$\cos \psi_2 = \rho/R_2$.

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